20 P,

GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

Memorandum

N64-24031
C

TO See Distribution 20p

DATE March 5, 1962
Memo M-AERO-A-12-62

FROM Aerodynamic Design Section, M-AERO-AA

Code 1 cat. 04
TMX 51710

SUBJECT Response of Spherical Balloon To Wind Gusts

1. The feasibility of measuring large wind gradients, or shears, by tracking a spherical balloon with radar is being studied by M-AERO-G, Aerophysics and Astrophysics Branch. To support this study, this memo gives the computer simulated response of a particular balloon to different wind gusts at three different altitudes. These data are then compared to theoretical data obtained by the method of reference 1.

To find how closely a rising balloon will follow a swiftly changing horizontal wind (large wind gradient) the forces on the balloon must be found. Three forces act on the balloon:

N6

1. buoyancy, F_B
2. gravity, F_W
3. aerodynamic drag, F_D

2. The buoyancy force is equal to the weight of the air displaced by the balloon.

$$F_B = \rho_a(VOL)g \qquad (1)$$

where

ρ_a = density of air
VOL = volume of balloon
g = gravity constant

3. The gravity force is the weight of the balloon plus the weight of the gas inside the balloon. Helium was the gas used for this study. The balloon considered here is equipped with a pressure valve to keep the pressure differential across the balloon constant; therefore, the weight of the gas inside the balloon decreases as the balloon rises.

4/1/64

$$F_W = -(W_B + W_G) \qquad (2)$$

where

W_B = weight of balloon
W_G = weight of gas

OTS PRICE

XEROX $ 1.60

MICROFILM $ ______

The weight of the gas is found by using the equation of state and assuming the temperature of the gas is equal to the temperature of the atmosphere at any given altitude.

$$W_G = \frac{(P_a + \Delta P)VOL}{g\ R_G\ T_a} \qquad (3)$$

where

P_a = atmospheric pressure
P_G = gas pressure
ΔP = $P_G - P_a$
R_G = gas constant
T_a = atmospheric temperature

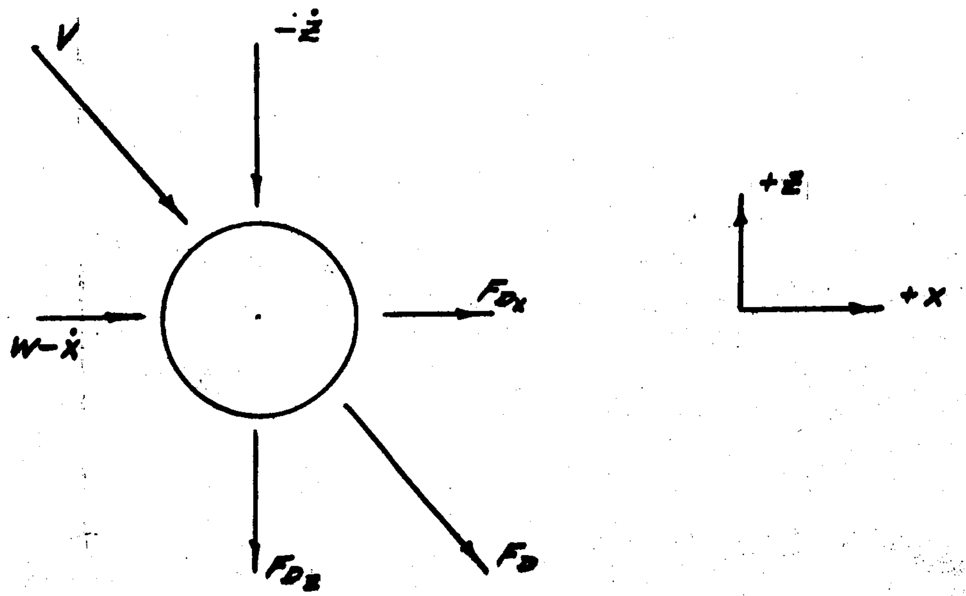
4. The aerodynamic drag force is given by the following formula:

$$F_D = 1/2\ \rho_a V^2\ A_{ref}\ C_D \qquad (4)$$

where

A_{ref} = maximum cross-sectional area of balloon
C_D = drag coefficient of balloon
V = velocity of relative wind

The relative wind is the resultant wind experienced by the balloon. This is shown in the diagram below. It is assumed throughout this study that the vertical components of winds are zero.



From this diagram, V is given as follows:

$$V = \sqrt{(w-\dot{x})^2 + \dot{z}^2} \tag{5}$$

where

w = horizontal velocity of wind
$\dot{x}$ = horizontal velocity of balloon
$\dot{z}$ = vertical velocity of balloon

The drag may be broken down into horizontal and vertical components.

$$F_{D_x} = 1/2\ \rho_a\ A_{ref}\ C_D\ V(w-\dot{x}) \tag{6a}$$

$$F_{D_z} = -1/2\ \rho_a\ A_{ref}\ C_D\ V\dot{z} \tag{6b}$$

The drag coefficient, C_D, is approximately a function of Reynolds number, Re; however, in the transition Re range the C_D is also highly a function of surface roughness and freestream turbulence. Due to the decrease in Re with increasing altitude, the balloon under study passes through the critical, or transition, Re range. Somewhere in this range the C_D suddenly increases with decreasing Re; after this sudden increase, the C_D remains fairly constant with decreasing Re until a Re of about 10,000 is reached, which is below the Re of interest in this study.

5. Figure 1 gives several experimental C_D versus Re curves. All these curves were obtained with low freestream turbulence except the variable density tunnel data which was very turbulent. It is seen that the effect of turbulence is to decrease the Re at which the sudden change in C_D occurs. Since the balloon under study passes through free air, the freestream turbulence is extremely small; therefore, the C_D transition is likely to take place at the higher values of Re shown in figure 1. The only curve in this group which is inconsistent with the others is the one obtained by drop testing in air. Notice that this curve has no sudden transition in C_D but increases gradually with decreasing Re. No other drop test data could be found, so this curve must remain in doubt. It would be informative to find a new drag curve using equation (7) and test data obtained from these balloon flights.

6. Since there is considerable differences in the C_D curves of figure 1, arbitrary constant values of drag were selected for this study. For Re larger than 500,000 C_D is assumed to be 0.09, a conservative value from the standpoint of response to wind. For Re less than 200,000 C_D was assumed to be 0.49. Between these two Re, C_D is very uncertain.

7. It was found in reference 2 by drop tests that any protuberance from the surface of the sphere caused very erratic C_D variations; however, the C_D of the sphere with protuberance was consistently higher than that of

a smooth sphere. Therefore, it would be advisable to put the pressure valve entirely inside the balloon and to make the juncture of the balloon and valve as smooth as possible.

8. Now, to find the vertical velocity of the balloon assuming no wind gusts, the resultant force in the z direction is zero.

$$F_B + F_W + F_{D_z} = 0$$

This equation yields the quasi-steady state (no vertical winds, no transient horizontal wind gusts) vertical velocity.

$$\dot{z} = \sqrt{\frac{2\left[\rho_a VOL\, g - \frac{(P_a + \Delta P)VOL}{g R_G T_a} - W_B\right]}{C_D A_{REF} \rho_a}} \qquad (7)$$

The vertical velocity as a function of altitude is found from equation (7) and plotted in figure 2. For a constant C_D of 0.09 the Re decreases from 17.86×10^5 at sea level to 5×10^5 at about 11.8 km. The C_D increases suddenly (see figure 1) somewhere between a Re of 5×10^5 and 2×10^5. Thus, from figure 2, the C_D increase occurs between about 11.8 and 15.4 km altitude, making the value of C_D highly uncertain in this altitude region. Above 11.8 km, the C_D is assumed to remain constant at 0.49. The maximum altitude of this balloon, from figure 2, is about 17.8 km.

9. To find the response of a balloon to a sharp gust, the transient forces on the balloon must be considered.

$$F_x = F_{D_x} = 1/2\ \rho_a A_{ref} C_D V(w-\dot{x}) \qquad (8a)$$

$$F_z = \rho_a(VOL)g - \frac{(P_a + \Delta P)VOL}{g\ R_G\ T_a} - w_B - 1/2\ \rho_a A_{ref} C_D V\dot{z} \qquad (8b)$$

Using these forces, the resulting accelerations are given.

$$\ddot{x} = \left[\frac{g \rho_a A_{REF} C_D}{2(W_G + W_B)}\right] V(W - \dot{x}) \qquad (9a)$$

$$\ddot{z} = \left[\frac{g^2 \rho_a VOL}{W_G + W_B}\right] - \left[\frac{g \rho_a A_{REF} C_D}{2(W_G + W_B)}\right] V\dot{z} - g \qquad (9b)$$

These formulas may be used over small time intervals to describe the motion of the balloon. This is conveniently done on a digital computer using some integration technique. The procedure used was to select a given wind profile and then compute the response of the balloon to this wind.

10. The characteristics of the balloon under consideration are given below:

material - aluminized mylar fabric (non-expansible)
diameter - 6 ft., 1.829 m
weight, W_B = 330 grams
gas - helium
ΔP = 8 millibars, 0.116 psi, 81.60 Kg/m^2

11. Three different gust profiles were selected corresponding to fairly large wind gradients. Walter Witty of Dynamics Analysis Branch, M-AERO-D, programmed the equations using the Runge-Kutta integration technique. The atmospheric properties P_a, ρ_a, T_a were assumed to remain constant throughout the gust. The initial vertical velocity, $\dot{z}$, was obtained from figure 2. The initial horizontal velocity does not affect the problem if $w - \dot{x} = 0$. Therefore, only the changes in $\dot{x}$, $\Delta\dot{x}$, and in w, Δw, from the starting point of the gust (t = 0) are used in the computation.

12. The gust profiles computed and their corresponding C_D's and altitudes are given in the figures listed below.

Figure	Altitude meters	Altitude feet	C_D	Wind Gradient m/sec/m
3	4,572	15,000	0.09	.14, (7/50)
4	4,572	15,000	0.09	.28, (14/50)
5	10,668	35,000	0.09	.14, (7/50)
6	10,668	35,000	0.09	.28, (14/50)
7	10,668	35,000	0.49	.28, (14/50)
8	10,668	35,000	0.49	.28, (7/25)
9	10,668	35,000	0.49	.92, (7/7.6)
10	16,764	55,000	0.49	.28, (14/50)

A few general remarks can be made about figures 3 through 10. The balloon horizontal velocity ($\Delta\dot{x}$) curve is remarkably similar to the wind profile in all cases, although the $\Delta\dot{x}$ curve is shifted upward slightly. The upward shift is not important. The vertical velocity does not change significantly over the small altitude changes involved here. The time increments used in the integration was 0.1 second for figures 8 and 9 and 0.5 second for the other figures. Thus figures 8 and 9 are more accurate than the other figures.

13. Comparing figures 3 through 10, it is seen that for a given C_D and altitude the balloon response to a wind gust improves as the wind gradient is decreased. Also, for a given altitude and wind gradient, the balloon response improves greatly as C_D increases. Thus, the response becomes better

after the increase in C_D. A lesser effect is the gradual decrease in response as altitude increases, for a given C_D and wind gradient.

14. A comparison will now be given between the computer simulated data and an analytical treatment (ref. 1) which makes two simplifying assumptions to obtain an equation for $w-\dot{x}$. Since the development of the equation is very brief, it will be repeated here.

15. Combining equations (9a) and (9b) the following equation is obtained.

$$w-\dot{x} = -\frac{(W_G+W_B)\ddot{x}\,\dot{z}}{(W_G+W_B)(\ddot{z}+g)-\rho_a \, Vol \, g^2} \qquad (10)$$

Now, assuming $\dot{z}$ is constant over the relatively short distance a gust acts (this was found to be a good assumption in figs. 3 through 10) the following equation is obtained.

$$w-\dot{x} = \frac{(W_G+W_B)\ddot{x}\,\dot{z}}{(W_G+W_B)g-\rho_a \, Vol \, g^2} \qquad (11)$$

Now, assume $(w-\dot{x})$ is constant for a given wind shear, S. It is seen from figs. 3 through 10 that this assumption is valid over most of the wind profile.

$$w-\dot{x} = K \qquad (12a)$$

$$\frac{dw}{dt} = \frac{d\dot{x}}{dt} = \ddot{x} \qquad (12b)$$

Now, S is defined as the change in horizontal wind with height.

$$S = \frac{dw}{dz} = \frac{dw}{dt}\frac{dt}{dz} = \frac{\ddot{x}}{\dot{z}} \qquad (13)$$

Substitution of equation (13) into (11) and replacing w by Δw and $\dot{x}$ by $\Delta\dot{x}$ yields the following equation, which is the desired equation.

$$\Delta w-\Delta\dot{x} = -\frac{(W_G+W_B)S\,\dot{z}^2}{(W_G+W_B)g-\rho_a \, Vol \, g^2} \qquad (14)$$

16. The vertical velocity, $\dot{z}$, may be found from figure 2 for any altitude to substitute into equation (14). Figure 11 shows equation (14)

plotted for 15,000 feet altitude and C_D of 0.09, and for 35,000 feet altitude and C_D of 0.09 and 0.49. The symbols indicate points obtained from figures 3 through 10 for the portion of the curves where $(\Delta w - \Delta\dot{x})$ was approximately constant. Figure 11 shows that equation (14) is valid in the region where the assumption, $w - \dot{x} = K$, is valid.

17. The quantity $(\Delta w - \Delta\dot{x})$ is of little practical importance, however. If the balloon velocity profile were exactly similar and equal in magnitude to — but shifted upward in altitude relative to — the wind profile, the radar would record the exact wind profile, although $w - \dot{x}$ at any given time would be non-zero.

A more important criterion is the difference between peaks, $(\Delta w_{peak} - \Delta\dot{x}_{peak})$ for a given wind gust. Figure 12 gives a comparison between $(\Delta w_{peak} - \Delta\dot{x}_{peak})$ from figures 3 through 10 and $(\Delta w - \Delta\dot{x})$ from equation (14). It is seen that equation (14) gives a conservative estimate of the quantity $(\Delta w_{peak} - \Delta x_{peak})$.

18. The conclusion reached from this study is that the balloon investigated in this memo responds sufficiently well to sharp wind gusts to make measurements of the gusts by radar feasible. If it is desired to correct the peaks of the measured wind speed, equation (14) will give a conservative correction.

Kenneth D. Johnston

Kenneth D. Johnston

APPROVED: W. Dahm

Werner K. Dahm
Chief, Aerodynamics Analysis Branch

Geissler

E. D. Geissler
Director, Aeroballistics Division

REFERENCES:

1. Leviton, Robert, A Detailed Wind Profile Sounding Technique, National Symposium on Winds for Aerospace Vehicle Design, H. G. Hanscom Field, Bedford, Massachusetts, Sept. 1961.

2. Bacon, David L., and Reid, Elliot, G., The Resistance of Spheres in Wind Tunnels and in Air, NACA Report No. 185, 1923.

DISTRIBUTION:

Dr. Geissler, M-AERO-DIR
Aerophysics & Astrophysics Branch, M-AERO-G (4)
Mr. Witty, M-AERO-D
Mr. Holderer, M-AERO-E
Mr. Dahm, M-AERO-A
Mr. Johnston, M-AERO-AA (2)

FIG. 1

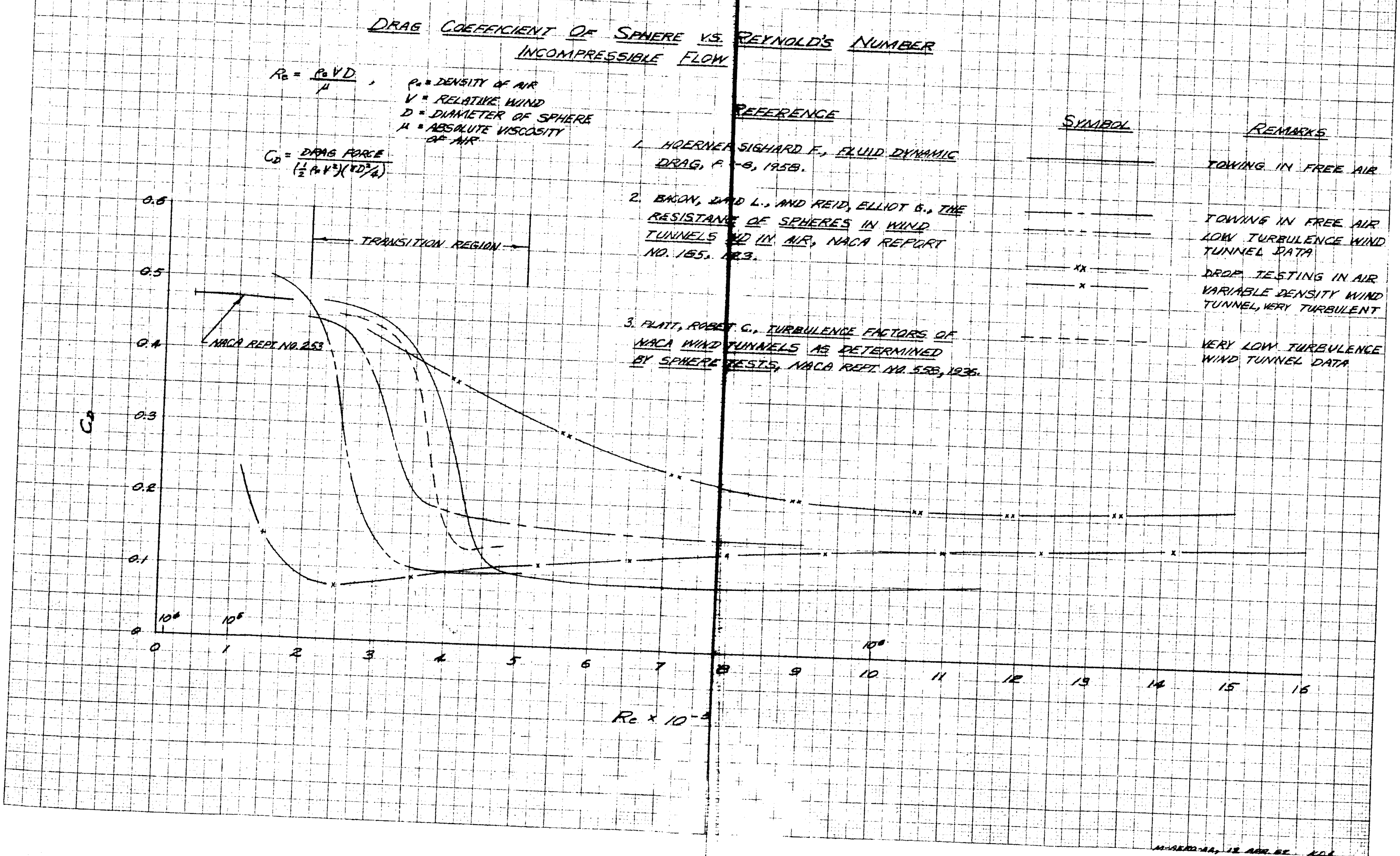

DRAG COEFFICIENT OF SPHERE VS. REYNOLD'S NUMBER
INCOMPRESSIBLE FLOW
$R_e = \frac{\rho_0 V D}{\mu}$,
ρ_0 = DENSITY OF AIR
V = RELATIVE WIND
D = DIAMETER OF SPHERE
μ = ABSOLUTE VISCOSITY OF AIR
$C_D = \frac{DRAG\ FORCE}{(\frac{1}{2}\rho_0 V^2)(\pi D^2/4)}$
REFERENCE
SYMBOL
REMARKS
1. HOERNER, SIGHARD F., FLUID DYNAMIC DRAG, F -8, 1958.
TOWING IN FREE AIR
2. BACON, D L., AND REID, ELLIOT G., THE RESISTANCE OF SPHERES IN WIND TUNNELS AND IN AIR, NACA REPORT NO. 185, 1923.
TOWING IN FREE AIR
LOW TURBULENCE WIND TUNNEL DATA
DROP TESTING IN AIR
VARIABLE DENSITY WIND TUNNEL, VERY TURBULENT
3. PLATT, ROBERT C., TURBULENCE FACTORS OF NACA WIND TUNNELS AS DETERMINED BY SPHERE TESTS, NACA REPT. NO. 558, 1936.
VERY LOW TURBULENCE WIND TUNNEL DATA
TRANSITION REGION
NACA REPT. NO. 253
C_D
0
0.1
0.2
0.3
0.4
0.5
0.6
10^4
10^5
10^6
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
$R_e \times 10^{-5}$
M-AERO-AA, 12 APR. 65 KDA

FIG. 2

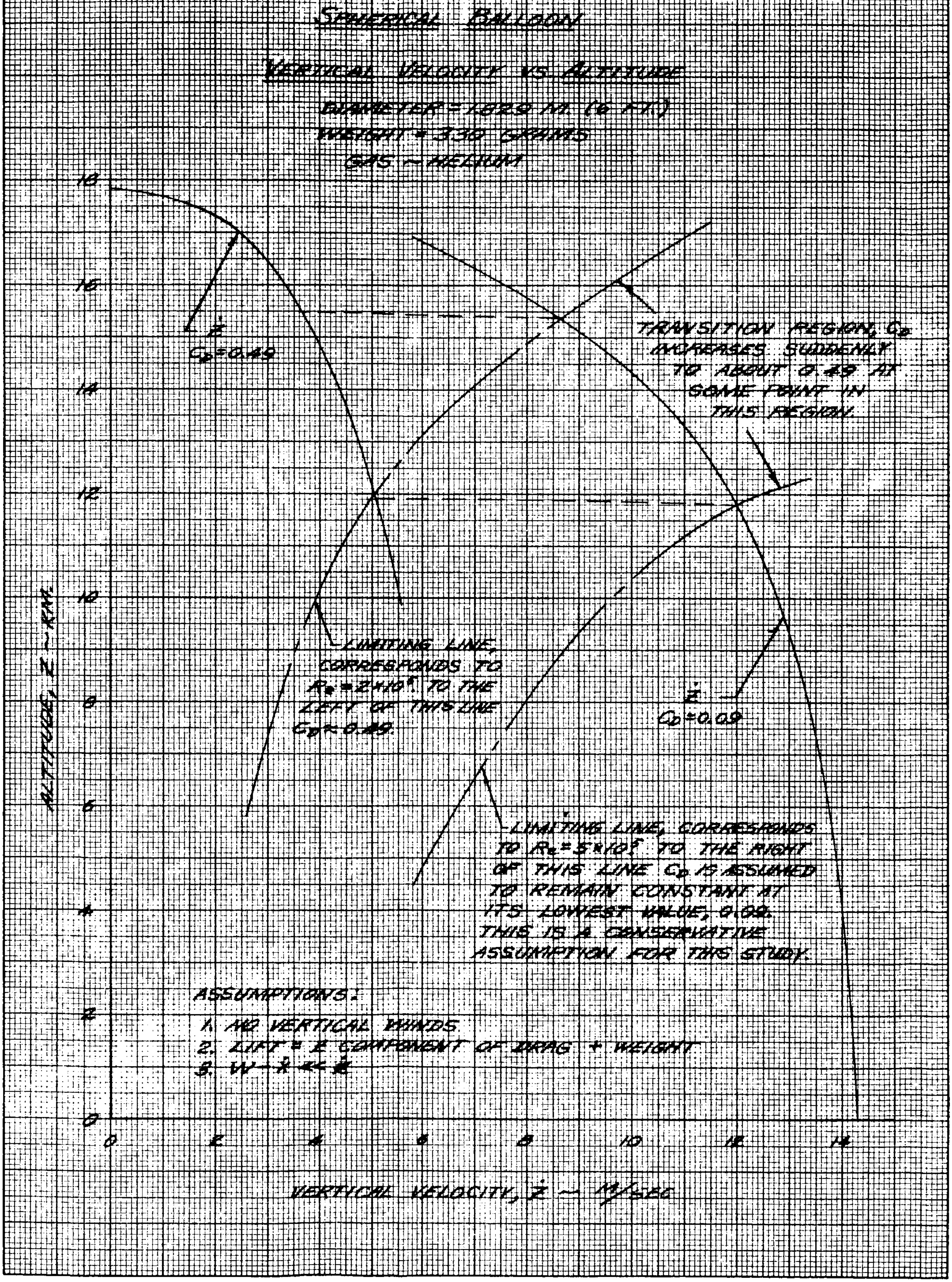

SPHERICAL BALLOON
VERTICAL VELOCITY VS ALTITUDE
DIAMETER = 1.829 M. (6 FT.)
WEIGHT = 330 GRAMS
GAS ~ HELIUM
ż
C_D = 0.49
TRANSITION REGION, C_D INCREASES SUDDENLY TO ABOUT 0.49 AT SOME POINT IN THIS REGION.
LIMITING LINE, CORRESPONDS TO $R_e = 2 \times 10^5$. TO THE LEFT OF THIS LINE $C_D \approx 0.49$.
ż
C_D = 0.09
LIMITING LINE, CORRESPONDS TO $R_e = 5 \times 10^5$. TO THE RIGHT OF THIS LINE C_D IS ASSUMED TO REMAIN CONSTANT AT ITS LOWEST VALUE, 0.09. THIS IS A CONSERVATIVE ASSUMPTION FOR THIS STUDY.
ASSUMPTIONS:
1. NO VERTICAL WINDS
2. LIFT = Z COMPONENT OF DRAG + WEIGHT
3. $W - \dot{x} \ll \dot{z}$
ALTITUDE, Z ~ KM.
0
2
4
6
8
10
12
14
16
18
VERTICAL VELOCITY, ż ~ M/SEC
0
2
4
6
8
10
12
14

FIG. 3

RESPONSE OF BALLOON TO WIND SHEAR

ALTITUDE = 4572 METERS (15,000 FT.)
WIND GRADIENT = 7 M/SEC/50 M.
$C_D = 0.09$

DIA. = 1.829 M. (6 FT.)
WEIGHT = 330 GRAMS
GAS ~ HELIUM

$\dot{z} \approx 13.9$ M/SEC

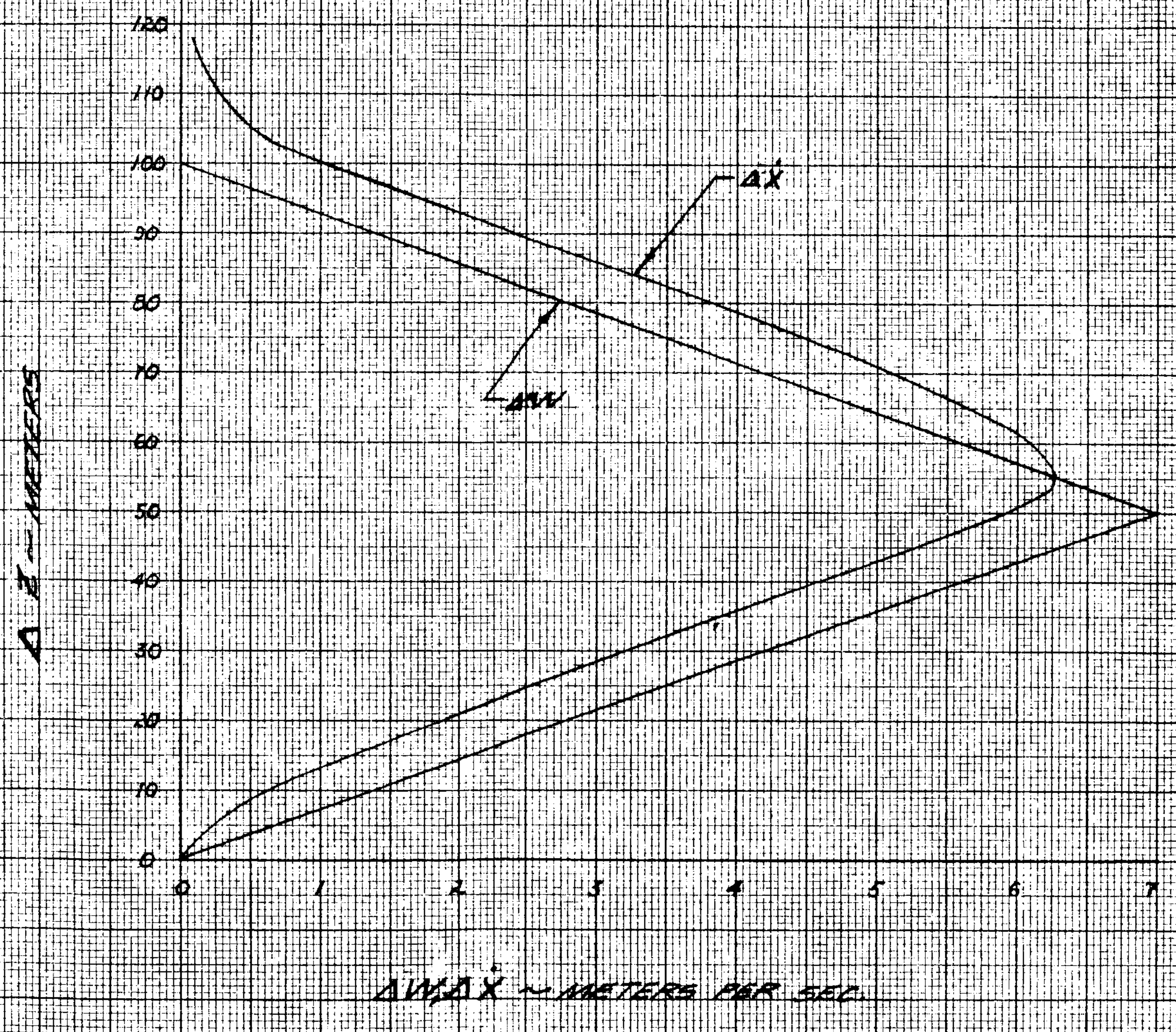


FIG. 4

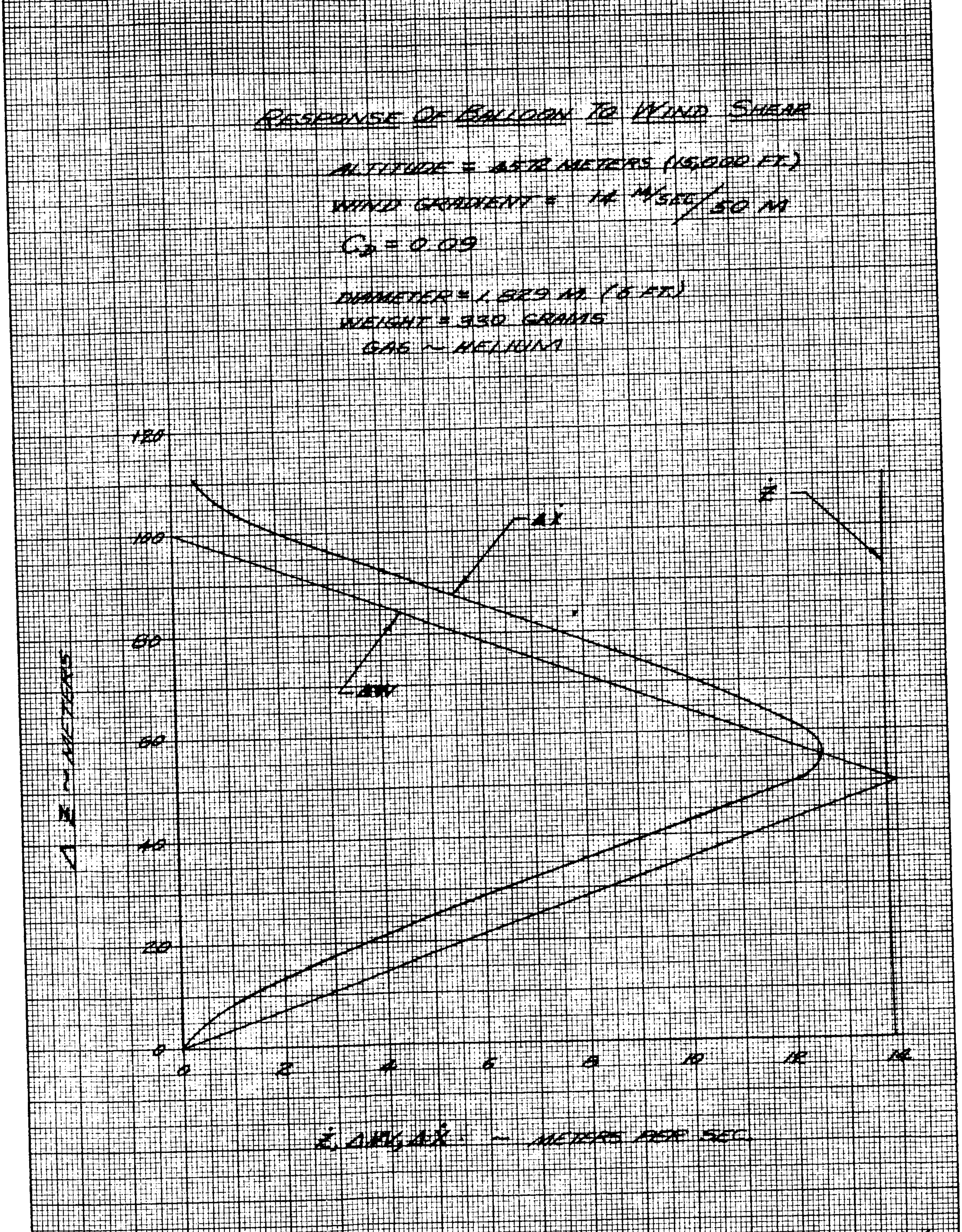

RESPONSE OF BALLOON TO WIND SHEAR
ALTITUDE = 4572 METERS (15,000 FT.)
WIND GRADIENT = 14 M/SEC/50 M
C_D = 0.09
DIAMETER = 1.829 M. (6 FT.)
WEIGHT = 330 GRAMS
GAS ~ HELIUM
Ż
ΔẊ
ΔW
ΔZ ~ METERS
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
Ż, ΔW, ΔẊ ~ METERS PER SEC.

FIG. 5

RESPONSE OF BALLOON TO WIND SHEAR

ALTITUDE = 10,668 METERS (35,000 FT.)
WIND GRADIENT = 7 M/SEC/50 M

$C_D = 0.09$

DIA = 1.829 M. (6 FT.)
WEIGHT = 330 GRAMS
GAS ~ HELIUM

$\dot{Z} \cong 12.5$ M/SEC

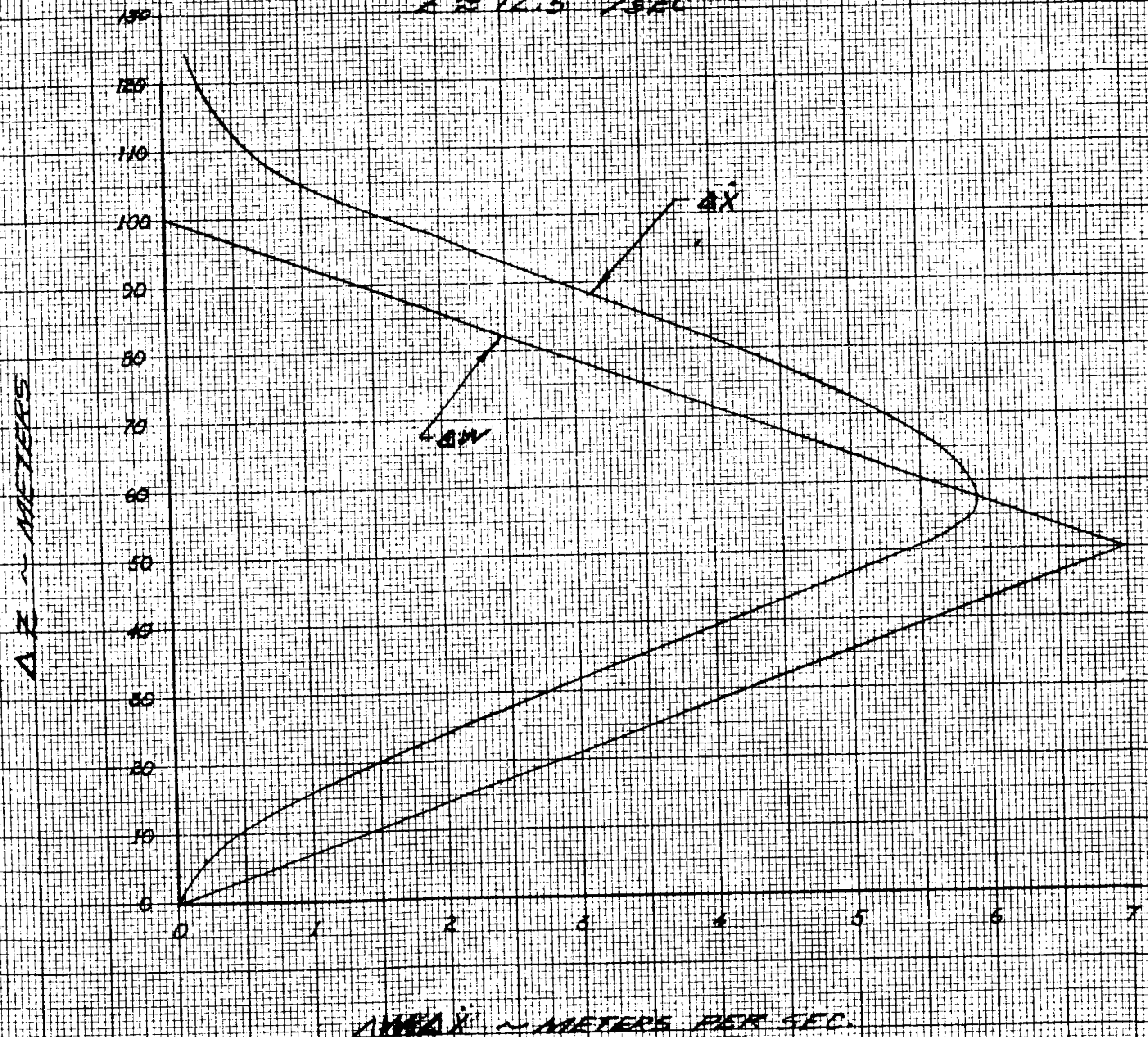


FIG. 6

RESPONSE OF BALLOON TO WIND SHEAR

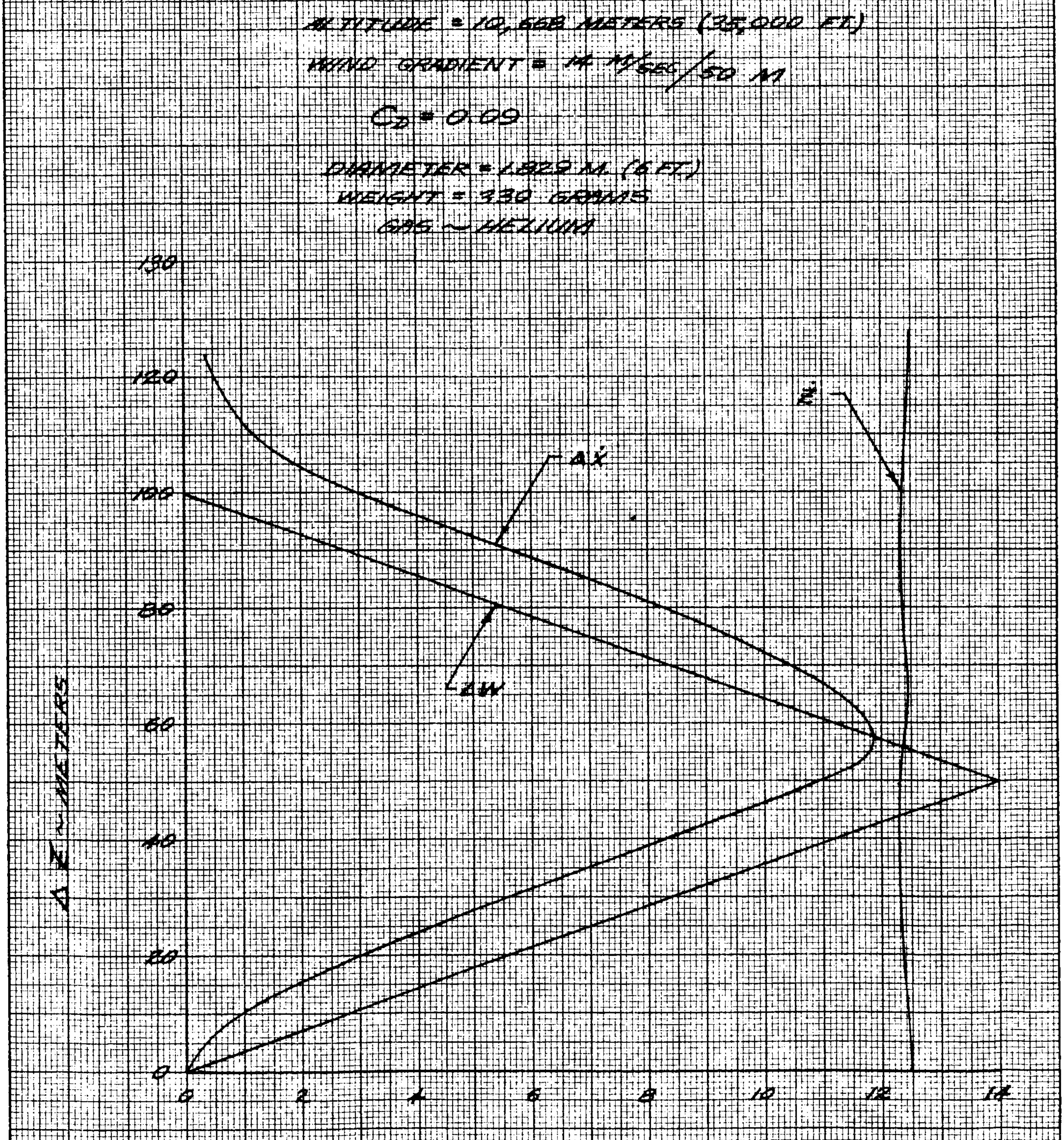
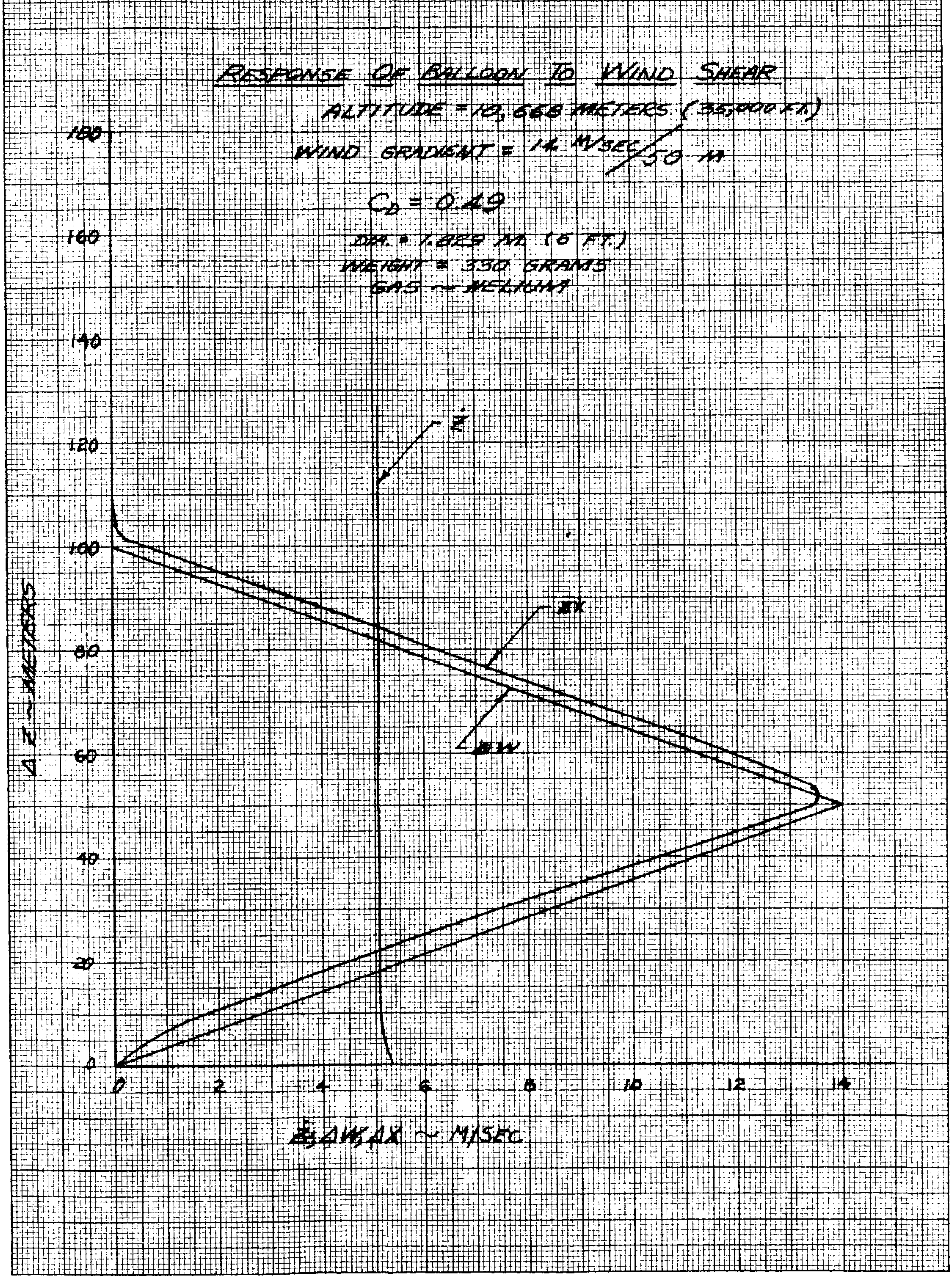


FIG.



RESPONSE OF BALLOON TO WIND SHEAR
ALTITUDE = 10,668 METERS (35,000 FT.)
WIND GRADIENT = 14 M/SEC / 50 M
C_D = 0.49
DIA. = 1.829 M. (6 FT.)
WEIGHT = 330 GRAMS
GAS ~ HELIUM
ΔZ ~ METERS
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
ΔW, ΔX ~ M/SEC

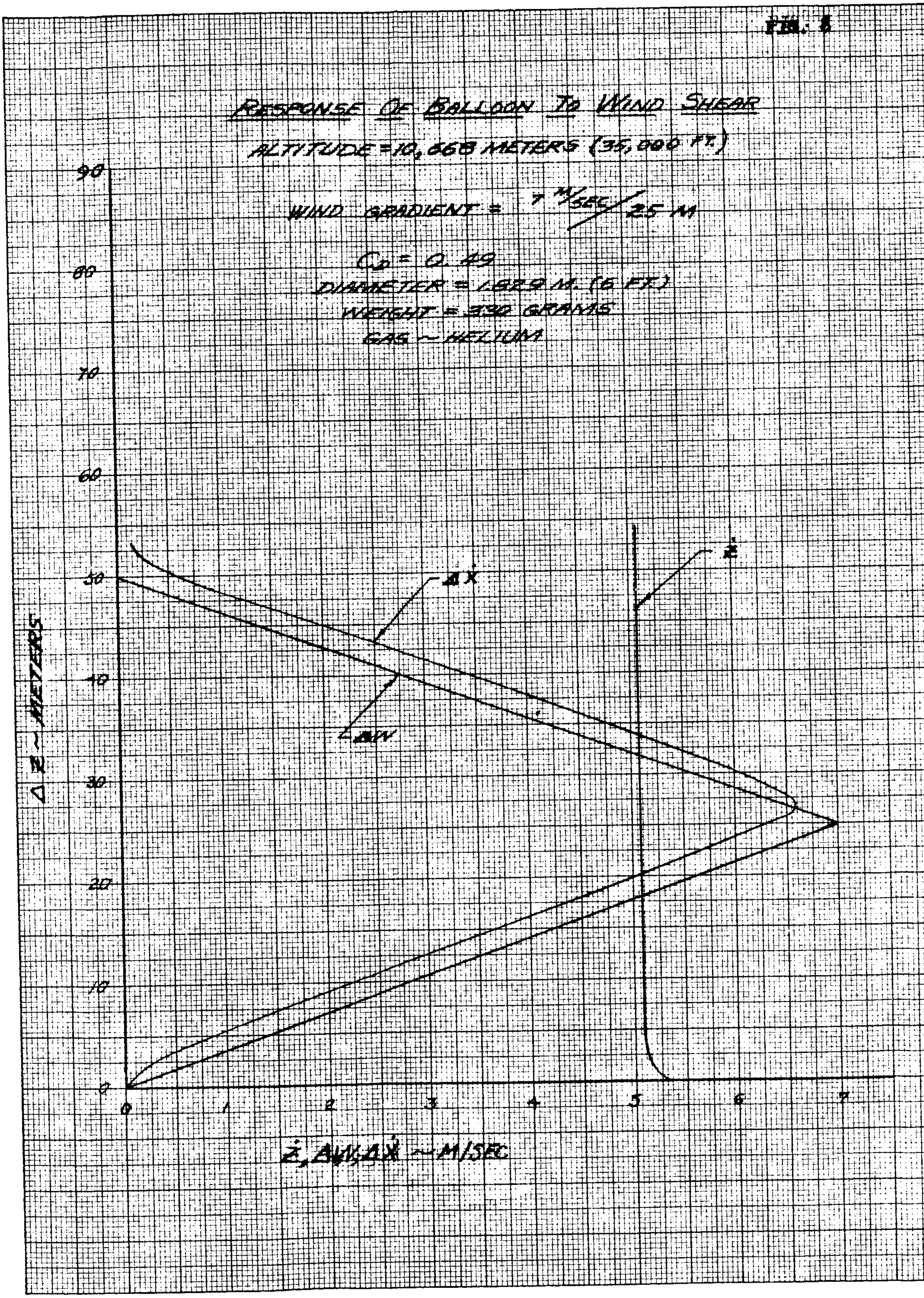


FIG. 8
RESPONSE OF BALLOON TO WIND SHEAR
ALTITUDE = 10,668 METERS (35,000 FT.)
WIND GRADIENT = 7 M/SEC / 25 M
C_D = 0.49
DIAMETER = 1.829 M. (6 FT.)
WEIGHT = 330 GRAMS
GAS ~ HELIUM
$\Delta \dot{X}$
$\dot{Z}$
ΔW
ΔZ ~ METERS
0
10
20
30
40
50
60
70
80
90
0
1
2
3
4
5
6
7
$\dot{Z}$, ΔW, $\Delta \dot{X}$ ~ M/SEC

FIG. 9

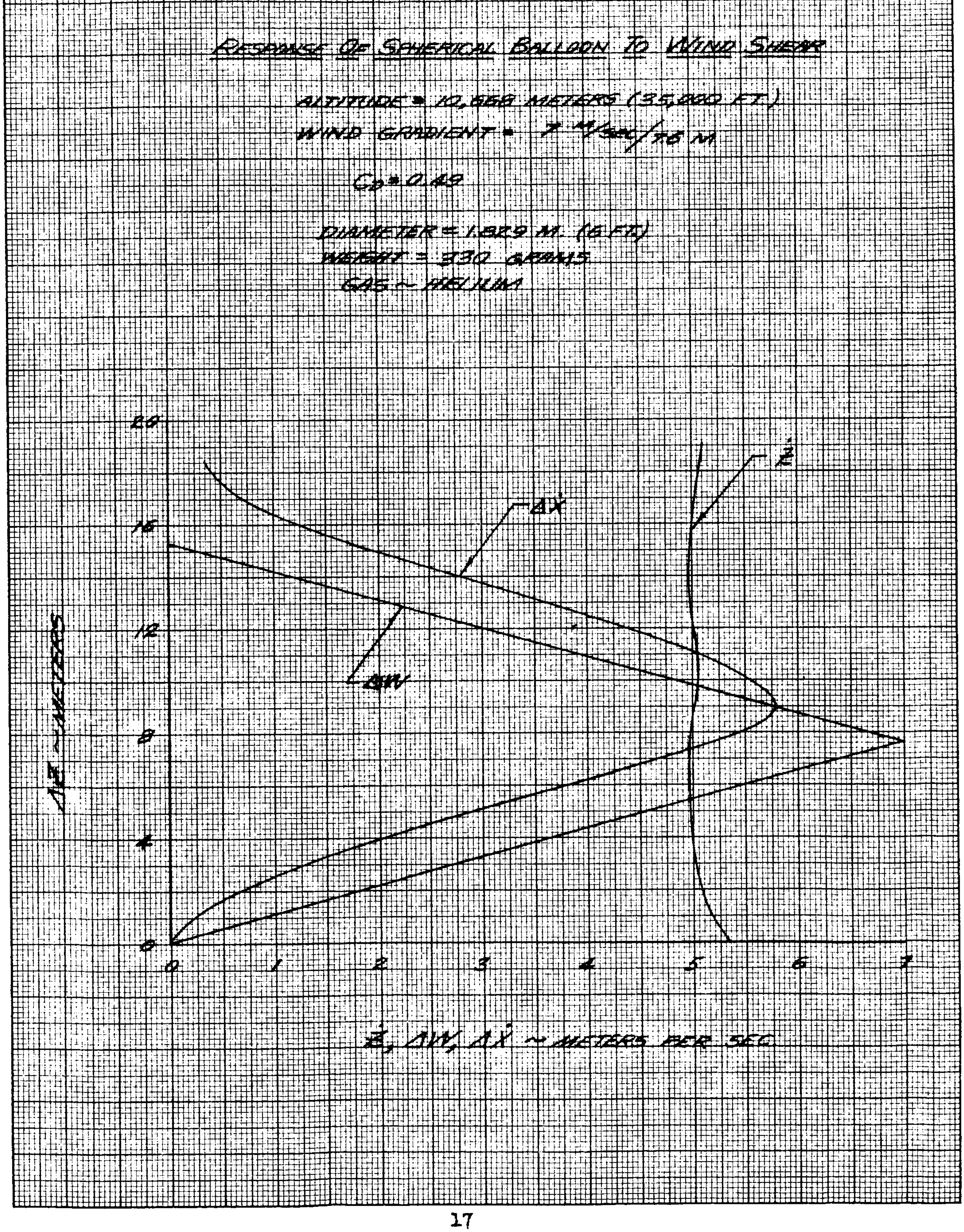
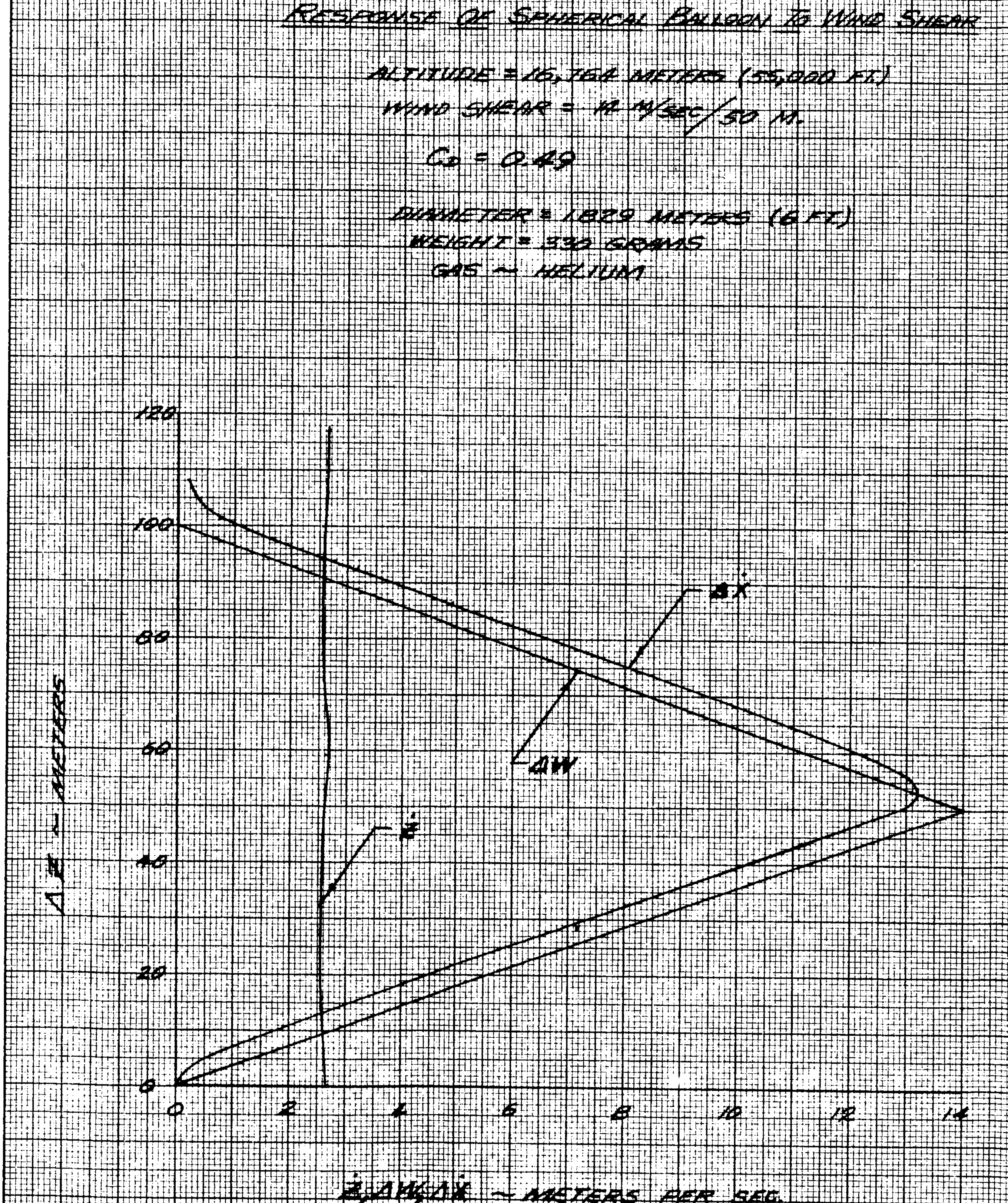
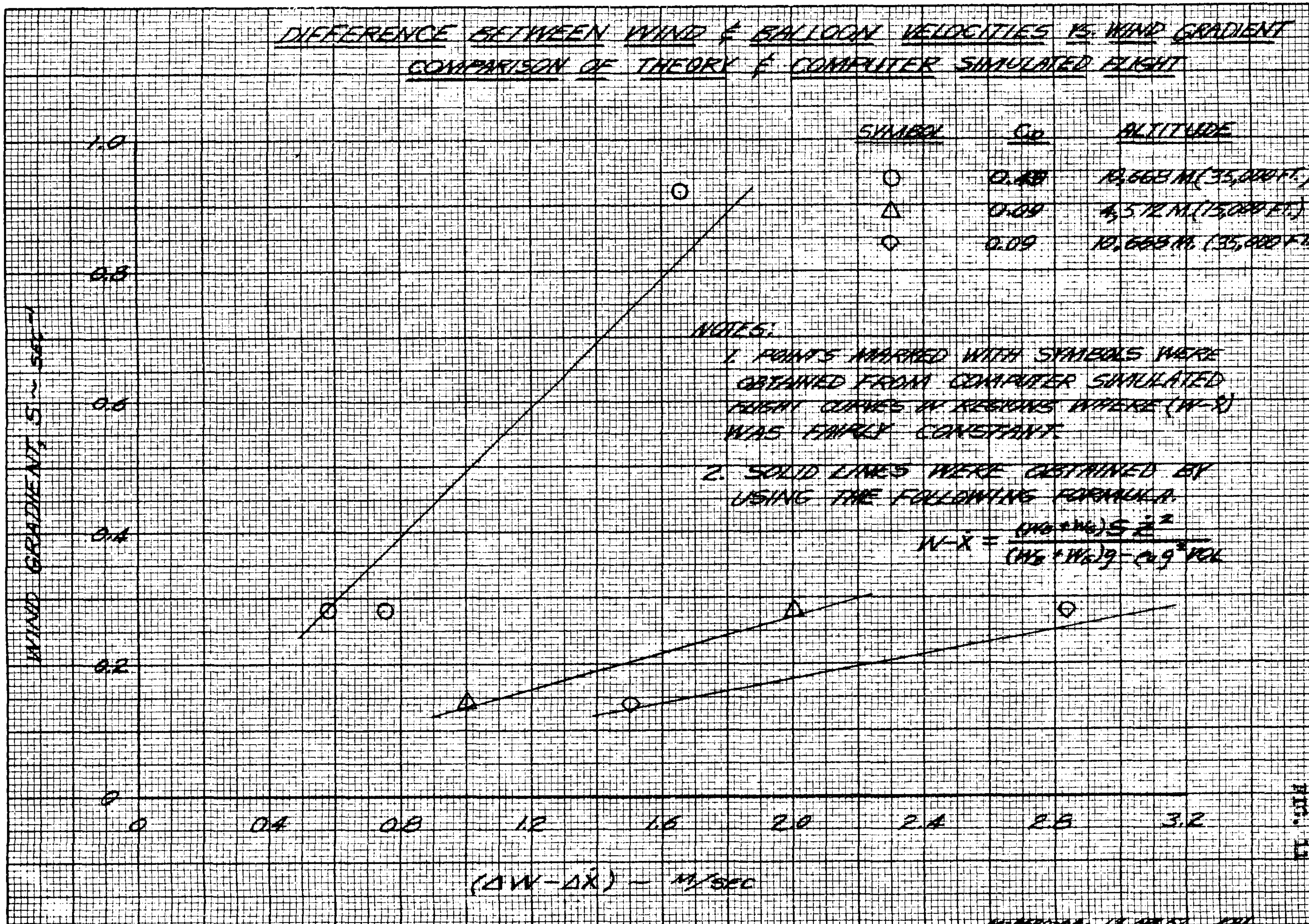

RESPONSE OF SPHERICAL BALLOON TO WIND SHEAR
ALTITUDE = 10,668 METERS (35,000 FT.)
WIND GRADIENT = 7 M/SEC/76 M
C_D = 0.49
DIAMETER = 1.829 M. (6 FT.)
WEIGHT = 330 GRAMS
GAS ~ HELIUM
ΔX
ΔW
Ż
ΔZ ~ METERS
Ż, ΔW, ΔẊ ~ METERS PER SEC
0
4
8
12
16
20
0
1
2
3
4
5
6
7

FIG. 10


RESPONSE OF SPHERICAL BALLOON TO WIND SHEAR
ALTITUDE = 16,764 METERS (55,000 FT.)
WIND SHEAR = 12 M/SEC/50 M.
CD = 0.49
DIAMETER = 1.829 METERS (6 FT.)
WEIGHT = 330 GRAMS
GAS ~ HELIUM
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
ΔẊ
ΔW
Ż
ΔZ ~ METERS
Ż, ΔW, ΔẊ ~ METERS PER SEC.



DIFFERENCE BETWEEN WIND & BALLOON VELOCITIES VS. WIND GRADIENT
COMPARISON OF THEORY & COMPUTER SIMULATED FLIGHT
SYMBOL
C_D
ALTITUDE
10,668 M. (35,000 FT.)
0.09
4,572 M. (15,000 FT.)
0.09
10,668 M. (35,000 FT.)
NOTES:
1. POINTS MARKED WITH SYMBOLS WERE OBTAINED FROM COMPUTER SIMULATED FLIGHT CURVES IN REGIONS WHERE $(W-\dot{X})$ WAS FAIRLY CONSTANT.
2. SOLID LINES WERE OBTAINED BY USING THE FOLLOWING FORMULA.
1.0
0.8
0.6
0.4
0.2
0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
WIND GRADIENT, S ~ SEC⁻¹
$(\Delta W - \Delta \dot{X})$ — M/SEC

FIG. 11

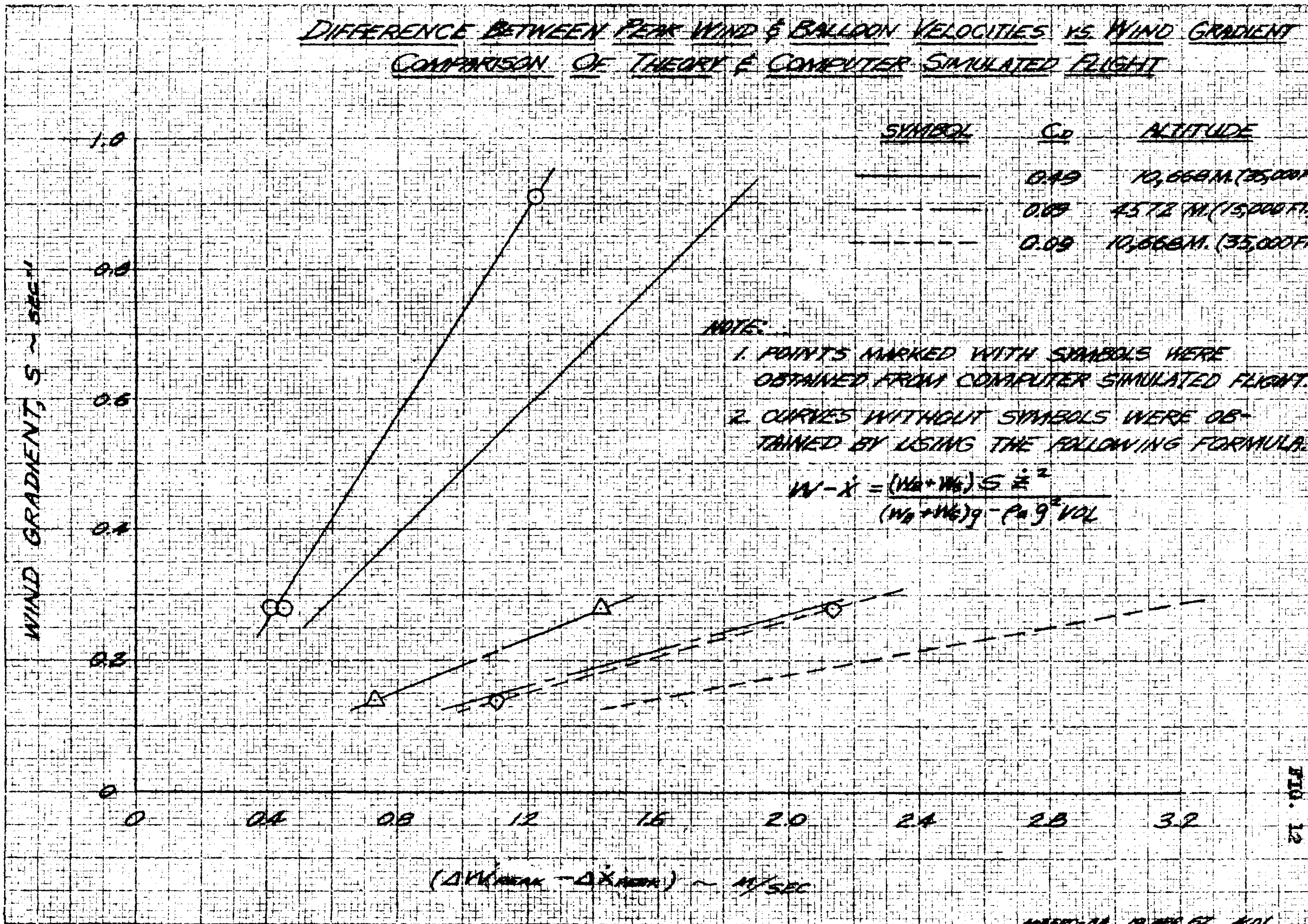

DIFFERENCE BETWEEN PEAK WIND & BALLOON VELOCITIES VS. WIND GRADIENT
COMPARISON OF THEORY & COMPUTER SIMULATED FLIGHT
SYMBOL
C_D
ALTITUDE
0.49
10,668 M. (35,000 FT.)
0.89
4572 M. (15,000 FT.)
0.09
10,668 M. (35,000 FT.)
NOTE:
1. POINTS MARKED WITH SYMBOLS WERE OBTAINED FROM COMPUTER SIMULATED FLIGHT.
2. CURVES WITHOUT SYMBOLS WERE OBTAINED BY USING THE FOLLOWING FORMULA.
$W-\dot{X} = \frac{(W_B+W_G) S \dot{Z}^2}{(W_B+W_G)g - \rho_a g^2 VOL}$
1.0
0.8
0.6
0.4
0.2
0
WIND GRADIENT, S ~ SEC^{-1}
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
$(\Delta W_{PEAK} - \Delta \dot{X}_{PEAK})$ ~ M/SEC
MSFC-AERO-AA, 19 MAR 62

FIG. 12